THIN FILM FERROELECTRIC TUNABLE DEVICES FOR RECONFIGURABLE RADIOS

Xinen Zhu, Jia Shiang Fu, Victor Lee, and Amir Mortazawi
Electrical Engineering and Computer Science Department
University of Michigan
Ann Arbor, MI 48109, USA

ABSTRACT

In this paper, a summary of our work in the area of tunable microwave circuits based on thin film ferroelectrics is presented. First, a technique is introduced to improve the linearity of thin film ferroelectric tunable capacitors. Measurements show an improvement in the 3rd order intermodulation point at the input (IIP3) of 16 dB. Next, the design and fabrication of an impedance tuner employing thin film ferroelectric capacitors for applications in adaptive matching networks is described. An impedance tuning ratio of 4:1 was achieved. Lastly, the fabrication of a switchable thin film bulk wave acoustic resonator (FBAR) and its application in the design of switchable filters are discussed. The resonator is measured to have a series resonance of 1.975 GHz with a Q factor of 233 and a parallel resonance of 2.035 GHz with a Q factor of 218. The resonator is proposed to construct a switchable bandpass filter.

1. INTRODUCTION

The number of wireless communication systems is constantly increasing as the number of free carrier frequencies shrinks, requiring an ever increasing improvement on system performance. Communication systems need not only improve functionality, but reliability as well. Thin film ferroelectrics based circuit components are a technology that can improve reliability and functionality of wireless communication systems. Circuits using thin film ferroelectrics have the potential of lowering the costs and improving the performance of frequency agile communication systems. Such systems could have an adaptive carrier frequency which adjusts to achieve minimum communication interference. Thin film ferroelectrics in general have good long term stability and reliability, low losses and insignificant dispersion. This technology can improve the functionality of wireless communication systems by their use for making integrated tunable circuit components with low loss, high Q factor, and low control voltage.

Ferroelectric materials, such as barium strontium titanate (BST), are ceramics that exhibit a temperature dependent high permittivity. The permittivity of the material experiences its most significant change at its Curie temperature, as shown in Fig. 1. When the temperature of ferroelectrics rise above the Curie temperature, their crystalline structure transitions from the ferroelectric to the paraelectric structural phase. For example, the unit cell of barium titanate (BTO), as represented in Fig. 2(a), changes from tetragonal to cubic when the temperature rises above 116ºC. In the ferroelectric phase, the polarization of a ferroelectric shows a hysteresis effect and therefore shows a spontaneous polarization at equilibrium. Strontium titanate (STO) is a material in the same class as BTO. However, at room temperature, it is in the paraelectric phase and therefore does not show hysteresis. For BST, the Curie temperature of the material depends on the ratio of barium to strontium. In this work, $Ba_{0.5}Sr_{0.5}TiO_3$, which is paraelectric at room temperature, is employed. The permittivity of ferroelectric materials is also dependent on applied electric field. The tunability curve of a ferroelectric capacitor is shown in Fig. 2(b).

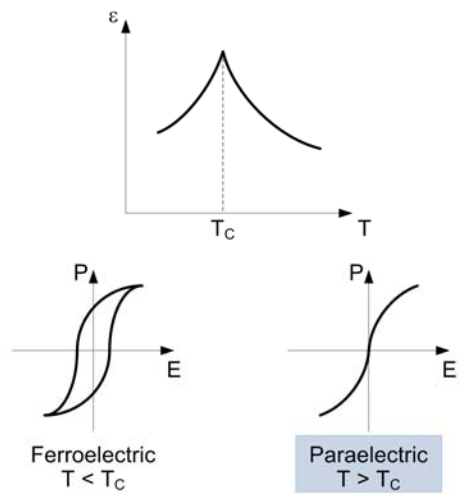


Fig. 1. Temperature dependent behavior of the permittivity (ε) of ferroelectric materials as well as its polarization (P) dependent behavior on electric field (E) for its ferroelectric and paraelectric phase.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 2008**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Thin Film Ferroelectric Tunable Devices For Reconfigurable Radios**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Electrical Engineering and Computer Science Department University of Michigan Ann Arbor, MI 48109, USA**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

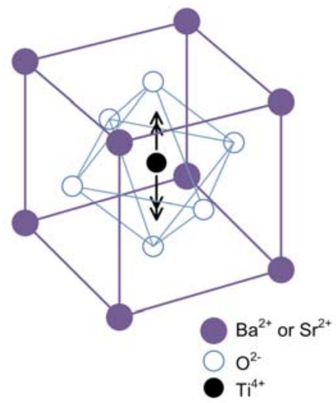
13. SUPPLEMENTARY NOTES
See also ADM002187. Proceedings of the Army Science Conference (26th) Held in Orlando, Florida on 1-4 December 2008, The original document contains color images.

14. ABSTRACT

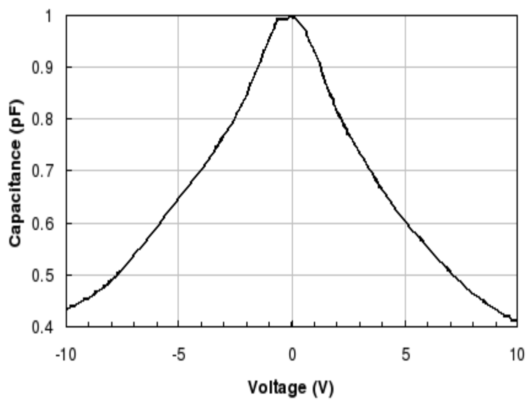
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18



(a)



(b)

Fig. 2. BST (a) cell structure and (b) capacitance-voltage curve.

The properties of ferroelectrics make them very desirable in fabricating tunable capacitors and high density DRAMs. In thin film form, ferroelectrics have properties that differ from that of bulk form. Thin film ferroelectrics in general have a much lower permittivity with an insignificant temperature dependence, making them quite ideal for use in RF applications. They are commonly deposited using RF sputtering, pulsed laser deposition (PLD), and metal-organic vapor phase epitaxy (MOCVD). Material characteristics are also very dependent upon the deposition technique.

The high, electric field dependent permittivity and low loss of thin film ferroelectrics make them ideal dielectric materials for voltage tunable capacitors or varactors. Compared to semiconductor diode varactors, ferroelectric varactors have a higher power handling capacity with a potential to achieve higher Q factors. Compared to competing MEMS based varactors, ferroelectrics varactors are smaller, have a faster response time, and have excellent power handling capabilities. Ferroelectrics are nonlinear, but there are techniques that can be used to improve linearity of ferroelectric varactors, one of which will be discussed later in this paper.

Another important property of ferroelectric materials is their electrostrictive response. Electrostriction can be thought of as field-induced piezoelectricity. FBARs using thin film ferroelectrics can be turned on and off with application of a bias voltage. Therefore ferroelectric materials can be employed in the design of switchable filter banks in frequency agile radios.

This paper summarizes the research work of our group on thin film ferroelectric technology for tunable microwave components and circuits. It includes a linearity-improving technique for ferroelectric varactors, a tunable matching circuit, and a switchable ferroelectric FBAR and its application in switchable filter design.

2. IMPROVING LINEARITY OF FERROELECTRIC VARACTORS

Ferroelectric materials are inherently nonlinear and therefore can generate harmonics and intermodulation products. Different approaches have been proposed to improve the linearity of ferroelectric capacitors (Yoon et al., 2003; York, 2004; Fu et al., 2006; Katta et al., 2006, Fu et al., 2007).

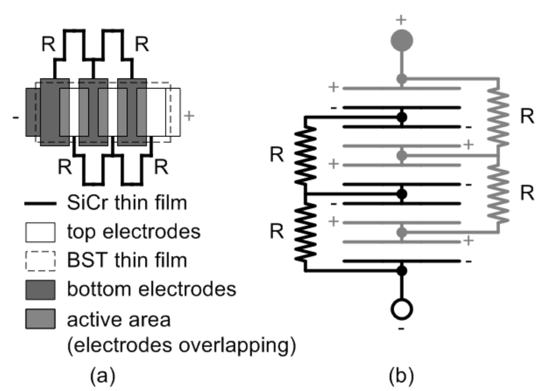


Fig. 3. A 5-stacked example for the proposed device architecture: (a) simplified layout, (b) schematic illustration (Fu et al., 2006).

The basic concept employed here to improve the linearity of ferroelectric varactors is based on reducing the RF voltage swing across them through interconnection of multiple capacitors in series. To maintain the tunability, large resistors are used to link varactor's the top and bottom electrodes so that equal biasing voltages are provided to every single capacitor in the stack. The simplified layout and schematic of a 5-stacked example are shown in Fig. 3(a) and (b), respectively.

Various tradeoffs that must be considered when designing stacked capacitors include Q factor, tuning speed versus the number of elements. Ideally, it is possible to preserve the Q factor of the multiple-stacked capacitors. However, the biasing resistors would inevitably introduce losses, degrading the Q factor. To reduce the degradation in the Q factor, one should set the biasing resistance as high as possible while satisfying the tuning speed requirement. In general, one should use the least number of elements that achieves the desired level of linearity to maintain high Q factors and tuning speeds.

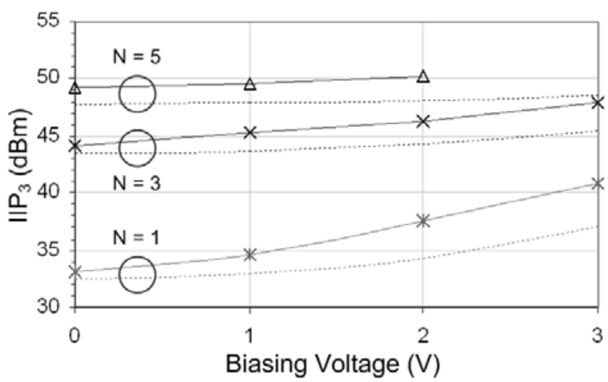


Fig. 4. Simulated (dash) and measured (solid) IIP_3 for N = 1, 3, and 5 at various bias voltages (Fu et al., 2007).

To demonstrate the effectiveness of the linearity-improving technique discussed, BST capacitors having the same capacitance (1.4 pF) but with different number of elements in series are fabricated and tested. A two-tone measurement is performed at 1.3 GHz with 1-MHz tone spacing. As shown in Fig. 4, the IIP_3 improvement of up to 16 dB is achieved as the number of elements increases from 1 to 5.

3. FERROELECTRIC-BASED IMPEDANCE TUNER

Impedance tuners are indispensible components in measurement setups for characterizing transistors such as load-pull and source-pull systems. They can also be used at the output of mobile transmitters for compensating antenna impedance variations due to nearby objects and human-body interaction. As shown in Fig. 5, an impedance tuner is used in an adaptive matching system to dynamically transform an unknown load impedance to match the system impedance. The impedance tuner is composed of a phase shifter and an impedance transformer. In this work, the general-purpose impedance tuner is designed based on all-pass networks (Fu et al., 2008).

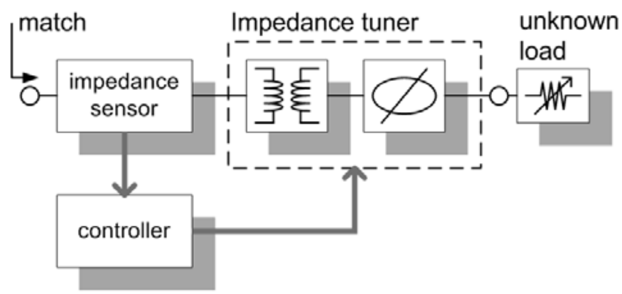


Fig. 5. Block diagram of an adaptive matching system (Fu et al., 2008).

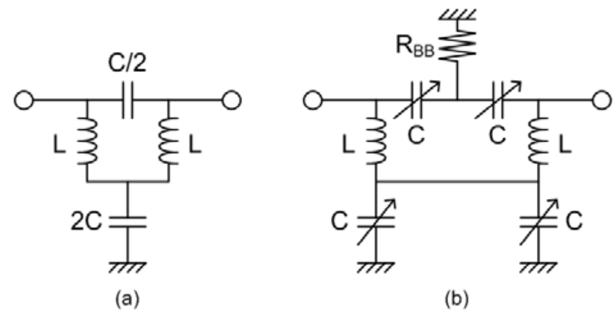


Fig. 6. (a) Generic all-pass network; (b) all-pass network incorporating varactors (Fu et al., 2008).

The schematics of a generic all-pass network and an all-pass network with varactors are shown in Fig. 6(a) and (b), respectively. By employing tuning elements such as varactors, the all-pass network can be used as a phase shifter. Furthermore, when designed at a different reference impedance, this type of phase shifter can also be used as an impedance transformer. In our work, both the phase shifter and the impedance transformer in the impedance tuner are designed based on the same all-pass network structure. Parallel-plate BST varactors are employed as the tuning elements in the impedance tuner.

The photograph of the fabricated impedance tuner is Shown in Fig. 7. The impedance tuner consists of a 2-section phase shifter and a 1-section impedance

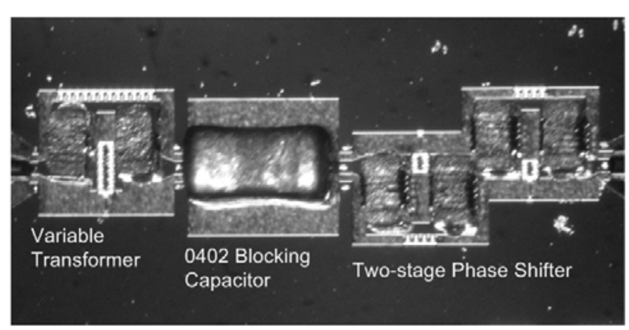


Fig. 7. Photograph of the fabricated impedance tuner. Circuit size: 4.3×1.2 mm^2 (Fu et al., 2008).

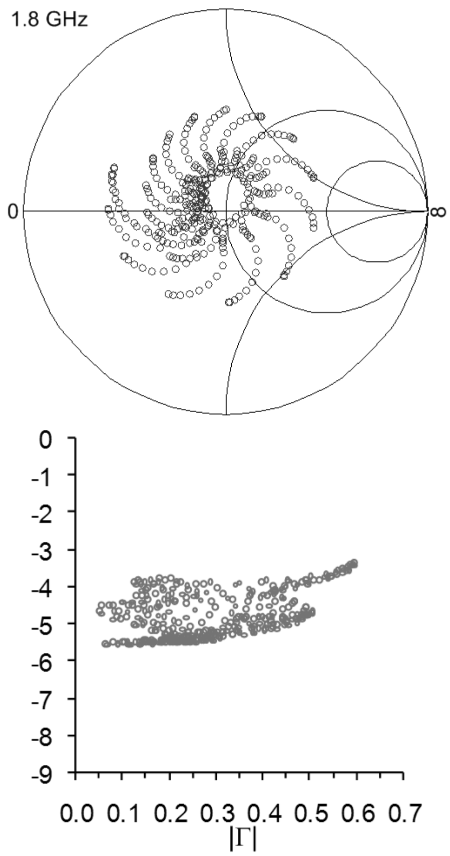


Fig. 8. Measured impedance coverage and dissipation loss versus magnitude of reflection coefficient |Γ| of the impedance tuner at 1.8 GHz (Fu et al., 2008).

transformer. The BST capacitors are fabricated on a 430-μm-thick sapphire substrate. A blocking capacitor is placed between the phase shifter and impedance transformer to isolate the biasing voltages. The biasing voltages for the impedance tuner are applied through the input and output microprobes.

The small-signal response of the impedance tuner is measured by sweeping the bias voltages for both the phase shifter and impedance transformer from 0 to 18 V. The impedance coverage and dissipation loss of the impedance tuner are shown in Fig 8. As can been seen, the maximum impedance transformation ratio of 4:1 (|Γ| = 0.6) is achieved.

4. FERROELECTRIC FBARS FOR USE IN SWITCHABLE CIRCUIT ELEMENTS

Ferroelectric FBARs are very promising for the design of switchable filter elements. They exhibit electrostrictive resonances which are controlled by the bias voltage applied across the device. In this work, several BST based FBARs have been fabricated and tested.

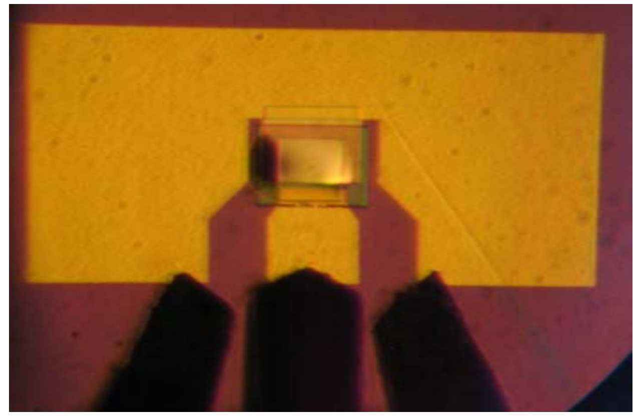
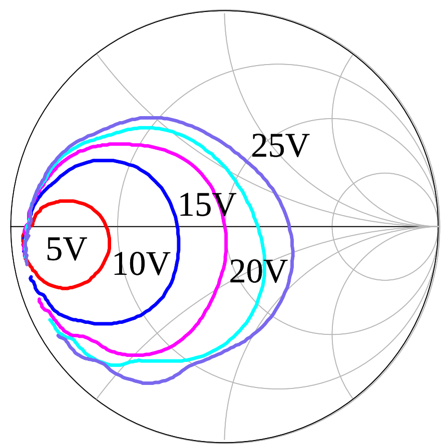


Fig. 9. Photograph of the fabricated BST FBAR (Zhu et al., 2007).



(b)

Fig. 10. BST FBAR device input impedances when DC bias applied to 25 V in 5 V step from 1.9 to 2.1 GHz (Zhu et al., 2007).

The BST FBAR is made on a 320-μm thick silicon substrate with a resistivity of 5 kΩ/□. Processing begins with the deposition of a 600-nm layer of SiO_2 to act as an etching barrier/buffer for a latter procedure. Next, the bottom electrode consisting of 10/1000 Å of Ti/Pt is deposited and patterned by evaporation and liftoff respectively. Afterwards, a BST thin film is deposited by pulsed laser deposition (PLD) technique using an excimer laser (λ = 248 nm, 25 ns pulse width, 10 Hz, ~1.75J/cm^2) with substrate temperature of 650°C in 300 mTorr oxygen environment. The resulting thickness is 730 nm. The top electrode is then deposited using the same technique as with the bottom electrode. After completing the processing of the parallel plate structure, the entire wafer is annealed at 500°C in flowing oxygen for 30 minutes to reduce the oxygen vacancies. The parallel plate structure is released using deep silicon reactive ion etching to etch away the portion of the substrate supporting the device. Lastly, the SiO_2 layer is removed by selective wet etching. A Photograph of the device is shown in Fig. 9.

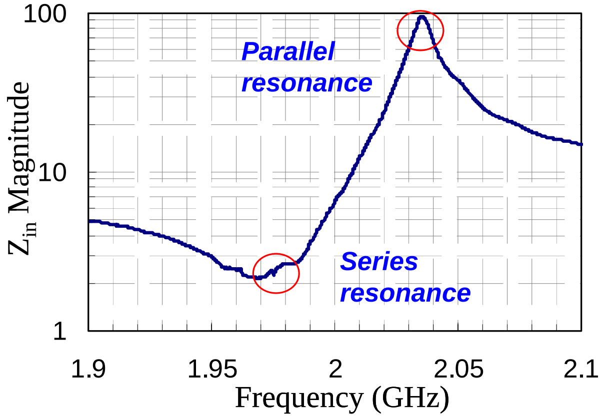


Fig. 11. Magnitude of the measured input impedance of the BST FBAR (Zhu et al., 2007).

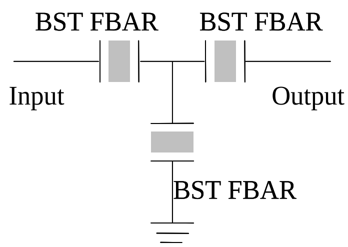
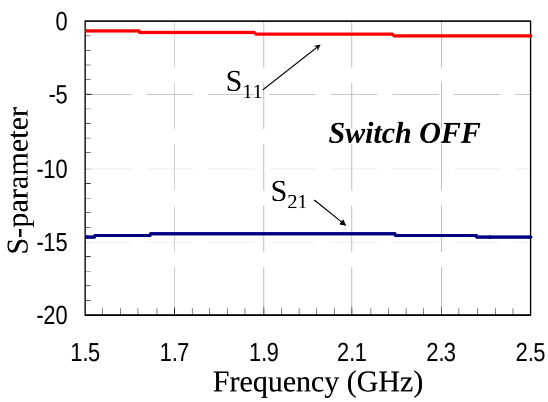
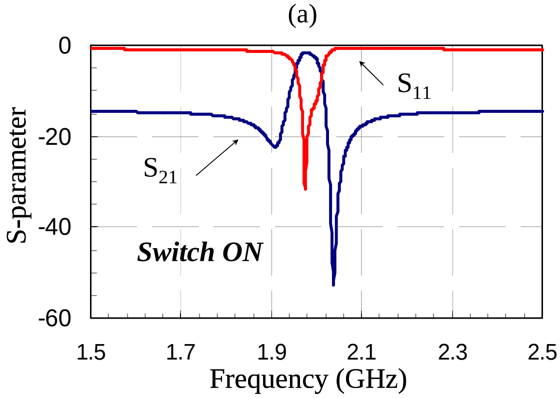


Fig. 12. BST FBAR filter block diagram.



(a)



(b)

Fig. 13. Simulated filter response (a) with zero DC bias and (b) with 25 V DC bias (Zhu et al., 2007).

Measurements are taken using a probe station equipped with a 150µm pitch GSG probe connected to an Agilent E8364B network analyzer. Without DC bias, no resonance is observed. When the DC bias is turned on and increased to 25 V in 5 V steps, the resonance is switched on and becomes stronger, as shown in Fig. 10. At 25 V, a series resonance is observed at 1.975 GHz with a Q factor of 233 and a parallel resonance at 2.035 GHz with a Q factor of 218 as shown in Fig. 11. Using the Modified Butterworth VanDyke circuit model, a 1.5 stage ladder type FBAR filter shown in Fig. 12 is simulated. The results show a band-pass filter with an insertion loss of 1.8 dB when on. The filter can be switched off by removing the bias voltage providing a rejection of 14.5 dB as shown in Fig. 13.

Using this device, one can achieve the function that previously can only be done by combining multiple filters and lossy RF switches. Therefore, the noise, loss, and cost can be reduced.

CONCLUSION

Ferroelectric varactors and FBARs have an excellent potential for the design of tunable elements in the frequency agile communication systems. Ferroelectric varactors have offer host of advantages such as, high permittivity for compactness, high power handling capability, fast tuning speed and potential integration with IC process. Ferroelectric FBARs exhibit electrostrictive resonances which can be utilized to design switchable resonators and filters. They are very promising in applications that require switchable filter banks.

Cascading many BST varactors can improve their linearity, making them suitable for high-power tunable radios which require low distortion. A ferroelectric-based impedance tuner is designed and fabricated for the adaptive matching applications, where the antenna mismatch due the interactions with nearby objects is dynamically compensated. At 1.8 GHz, the impedance tuner achieves 4:1 impedance transformation ratio. A switchable BST FBAR is fabricated with a series resonance at 1.975 GHz with a Q factor of 233 and a parallel resonance at 2.035 GHz with a Q factor of 218 at a dc bias of 25 volts.

These devices offer have the potential to greatly enhance the performance of frequency agile radios.

REFERENCES

Damjanovic, D., 1998: Ferroelectric, dielectric and piezoelectric properties of ferroelectric thin films and ceramics, *Rep. Prog. Phys.*, **61**, 1267-1324.

Fu, J.-S., Zhu, X., Chen, D.-Y., Phillips, J. D., and Mortazawi, A., 2006: A linearity improvement technique for thin-film barium strontium titanate capacitors, *2006 IEEE MTT-S Int. Microwave Symp. Dig.*, 560-563.

Fu, J.-S., Zhu, X., Phillips, J. D., and Mortazawi, A., 2007: Improving the linearity of ferroelectric-based microwave tunable circuits, *IEEE Trans. Microwave Theory & Tech.*, **55**, 354-360.

Katta, H., Kurioka, H., and Yashima, Y., 2006: "Tunable power amplifier using thin-film BST capacitors," in *2006 IEEE MTT-S Int. Microwave Symp. Dig.*, 564-567.

Tombak, A., 2000: Radio frequency applications of barium strontium titanate thin film tunable capacitors, Dept. of Electrical and Computer Engineering, North Carolina State University, 63 pp.

York, R. A., 2004: Circuit configuration for DC-biased capacitors, U.S. patent 6 674 321.

Yoon, Y.-K., Kim, D., Allen, M. G., and Kenney, J. S., 2003: A reduced intermodulation distortion tunable ferroelectric capacitor: architecture and demonstration, *2003 IEEE MTT-S Int. Microwave Symp. Dig.*, **3**, 1989-1992.

Zhu, X., Phillips, J. D., and Mortazawi, A., 2007: A DC voltage dependent switchable thin film bulk wave acoustic resonator using ferroelectric thin film, in *2007 IEEE MTT-S Int. Microwave Symp. Dig.*, 671-674.